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# GEOMETRIC- AND NON-GEOMETRIC MEAN SENSOR-ORIENTATION-INDEPENDENT SEISMIC INTENSITIES. APPLICATION TO THE ITALIAN STRONG MOTION DATABASE

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## ABSTRACT

In this paper, the directionality effects of the as recoded ground motions are investigated. The Italian accelerometric archive (ITACA) is used for this purpose. A number of 949 horizontal ground motion records (two components) are used. The following measures, resulting from different ways of combining the maximum values ($m_1$,$m_2$) of the two horizontal components were investigated: Geometric Mean (GMRot), projection (Rot) of the two as recorded components onto all non-redundant azimuths and larger (LRot) value [max($m_1$,$m_2$)]. The sensor-orientation-independent quantities: GMRotDpp, RotDpp, GMRotIpp and LRotDpp have been obtained. In these quantities, pp means percentile and D and I, respectively, mean dependent and independent of the period. The 50$^{th}$ percentiles values of these intensity measures were compared to the GM of the as-recorded components obtaining differences of 1% for GMRotD50 and in the ranges 2-6%, 1-2% and 15-27% respectively for RotD50, GMRotI50 and LRotD50. The three first ratios show a good agreement with similar studies in other regions. Moreover, the vector combination of the two orthogonal time histories (Root of the Sum of Squares, RSS) presents equal values as RotD100 and LRotD100. The study has also been performed by using the maxima of the time histories combinations; the following quantities are thus investigated: mGMRotDpp and mGMRotIpp, where *m* indicates peak values of the combined time histories. Our results indicate that the ratios between the 50$^{th}$ percentile of these orientation independent intensities and the GM of the as-recorded components, are in the ranges 0.78-0.85 and 0.79-0.86, respectively, proving that former ones are conservative.

*Keywords: Directionality; Intensity measures; Response spectra; Sensor-orientation-independent measures; Ground motion*

## 1. INTRODUCTION

Most of the Ground Motion Prediction Equations (GMPE) use the spectral response corresponding to the horizontal ground motions as intensity measure (IM) (Beyer and Bommer, 2006, Douglas, 2017). There are many ways to combine the two as recorded horizontal components in the GMPEs (Douglas, 2003, 2017), the most frequently used being the arithmetic mean (AM), the geometric mean (GM), the quadratic mean (QM) or the larger value of both components (Larger). In the GMPEs, the GM of the response spectra is the most commonly used IM. An advantage of the GM is that the variability of the results of the regressions used in the GMPEs is lower compared to other commonly employed measures (Beyer and Bommer, 2006). However, the GM of the response spectra has a potentially significant drawback: it is not invariant to sensor orientation so, the measure may differ for the same earthquake, depending on the orientation of the recording instrument.

As an extreme case, let's consider a free noise, linearly polarized signal. If one of the sensors is aligned with the direction of polarization, the response spectrum of the ground motion registered would be zero. This is an essential consideration for records of near-fault earthquakes, where the rupture orientation and the radiation pattern, including the directivity effects, can produce strong motions correlated for 1 s

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or more periods (Spudich *et al*., 2004).
For this reason, different sensor orientation-independent measures have been recently used, such as: GMRotDpp, GMRotIpp, RotDpp and RotIpp (Boore *et al.*, 2006 and Boore, 2010), where "pp" represents the percentile, commonly 50, and letters D and I indicate dependent or independent of the period. By using these new measures, the sensor orientation effect is eliminated as a component of epistemic uncertainty, which may be important in probabilistic calculations of seismic risk of soil movements with a small annual frequency of exceedance (Bommer *et al.*, 2004).
This work aims to evaluate the ground-motion directionality effects with the dataset from Italy and to propose new sensor-orientation-independent IMs, based on the Larger measure and on the prior combination of the responses of the horizontal components of acceleration for each time instant, instead of combining maximum values of the two horizontal components. These measures are LRotDpp, for the Larger measure and mGM, mGMRotDpp and mGMRotIpp, for the maxima of the prior combination of time histories.

## 2. SENSOR-ORIENTATION-INDEPENDENT INTENSITY MEASURES

The method to determine the different IMs proposed by Boore *et al.* (2006) and Boore (2010) has been adapted to the characteristics of the available dataset. Other procedures, oriented to characterize the available database and to the calculation of the response spectra, have been used too. For this study, acceleration response spectra with 5% of critical damping are used. The main IMs obtained by combining the two as recorded components are defined in the following.

### *2.1 Geometric-mean IMs*

The GM of the response spectra of two horizontal and orthogonal components (usually NS and EW) is defined as:

$$Sa_{GM}(T_i, \xi) = \sqrt{Sa_{NS}(T_i, \xi) \cdot Sa_{EW}(T_i, \xi)} \quad (1)$$

where $Sa_{GM}$ is the GM response spectra, $Sa_{NS}$ and $Sa_{EW}$ are spectral accelerations of the two horizontal components for period $T_i$ and critical damping factor ξ.
Due to the dependence of the sensor orientation angle in the GM of the spectral response as IM, Boore *et al.* (2006) define two ground-motion measures corresponding to a specific percentile of the set of GM obtained using all non-redundant rotations. These measures are: GMRotDpp and GMRotIpp, where “pp” represents the percentile, commonly “50”, and the letters D and I, indicate dependence or independence of the period.
For the calculation of these measures, linear combinations of the orthogonal components between 0 and 90 degrees of rotation are computed (Equations 2 and 3).

$$acc_1(\mathrm{t}, \theta) = \mathrm{acc}_{EW}(\mathrm{t}, 0)\ \cos\theta + \mathrm{acc}_{NS}(\mathrm{t}, 0)\ \sin\theta \quad (2)$$

$$acc_2(t, \theta) = -\mathrm{acc}_{EW}(t, 0)\ \sin\theta + \mathrm{acc}_{NS}(\mathrm{t}, 0)\ \cos\theta \quad (3)$$

where $\mathrm{acc}_{EW}(\mathrm{t}, 0)$ and $\mathrm{acc}_{NS}(\mathrm{t}, 0)$ corresponds to the as-recorded acceleration horizontal components, *t* is the time and $\theta$ is the rotation angle.
Linear combinations of the rectangular components between 0-90° are used because these combinations have a periodicity in this range. This fact can be seen when the value of peak ground acceleration (PGA) is calculated, which takes symmetric values from 90 degrees.
To determine GMRotDpp, the GM of the spectral response of the linear combinations (Equations 2 and 3) are calculated for all non-redundant angles with increments of 1°. Subsequently, the corresponding angle of the desired percentile “*pp*$^{th}$” is defined for each oscillator, thus sorting incrementally the values obtained for each rotation, not being feasible to have a single angle valid for all the periods, reason why it is said that this measure is period-dependent (D).
Although the GMRotDpp definition satisfies the requirement of being sensor orientation-independent,

it has the deficiency that a single rotation does not produce two-time series for which the GM of the individual response spectrum is equal to GMRotDpp for all considered periods. For this reason, GMRotIpp is calculated; that is, an independent-period measure. This measure is obtained from the angle that minimizes the dispersion of the GM, normalized by GMRotDpp, for a specific rotation angle, Equation 4. The angle for which the mean quadratic deviation is minimum is considered as the angle for which the error among the studied range of period is minimized, guaranteeing the similarity between GmRotDpp and GMRorIpp.

$$penalty(\theta) = \frac{1}{N_{per}} \sum_{i=1}^{h} \left[ \frac{Sa_{GM}(Ti, \xi, \theta)}{Sa_{GMRotDpp}(Ti, \xi)} - 1 \right]^2 \tag{4}$$

$$Sa_{GMRotIpp}(Ti, \xi) = Sa_{GM}(Ti, \xi, \theta_{min}) \tag{5}$$

where the range of usable periods are $T_1$ to $T_h$, $Sa_{GM}(Ti, \xi, \theta)$ is the GM of the response spectra for period $Ti$ computed for rotation angle θ, and $Sa_{GMRotDpp}(Ti, \xi)$ is the $pp^{th}$ percentile value of $Sa_{GM}(Ti, \xi, \theta)$ over all non-redundant angles with a critical damping factor ξ.

### *2.2 RotDpp*

RotDpp measure was introduced by Boore (2010) and is defined as the projection of the two as-recorded components rotated onto all nonredundant azimuths. The two acceleration components are combined using Equation 2 or 3 with increments of 1° in the range between 0 and 180°. Because the response spectrum is defined as the maximum of the absolute amplitude of the response of a single degree of freedom damped oscillator, this measure has a rotation-angle periodicity of 180°. Thus, the response spectrum is estimated for each increment. Once the 180 spectra are obtained, the spectral values are ordered for each oscillator period from lowest to highest for all the rotation angles and the $nn^{th}$ centile define the measure of ground motion for that oscillator period.

### *2.3 Root-sum-of-squares (RSS)*

Another IM of interest is the maximum response spectrum, RSS (Hidalgo-Leiva *et al.*, 2017), determined as the maximum value of the root-of-sum-of-squares of the time histories responses for each oscillator of a single degree-of-freedom damped system. The spectral values of RSS are defined as:

$$\ddot{u}_{RSS}(T_i, t_i, \xi) = \sqrt{[\ddot{u}_{NS}(T_i, t_i, \xi)]^2 + [\ddot{u}_{EW}(T_i, t_i, \xi)]^2} \tag{6}$$

$$\theta_{RSS}(T_i, t_i, \xi) = \tan^{-1} \left[ \frac{\ddot{u}_{NS}(T_i, t_i, \xi)}{\ddot{u}_{EW}(T_i, t_i, \xi)} \right] \tag{7}$$

$$Sa_{RSS}(T_i, \xi) = max|\ddot{u}_{RSS}(T_i, t_i, \xi)| \ \forall \ t_i \tag{8}$$

where $\ddot{u}_{EW}(T_i, t_i, \xi)$ and $\ddot{u}_{NS}(T_i, t_i, \xi)$ correspond to the acceleration time history responses of a damped single degree-of-freedom oscillator with period $T_i$, at time $t_i$, with a fraction of critical damping ξ. These two responses are used to obtain $\ddot{u}_{RSS}(T_i, t_i, \xi)$ and $\theta_{RSS}(T_i, t_i, \xi)$, time histories, which define the instantaneous modulus and phase angle corresponding to the vector defined by the two rectangular acceleration response components for each instant of time $t_i$. Then, $Sa_{RSS}(T_i, \xi)$ is defined as the maximum value of $\ddot{u}_{RSS}(T_i, t_i, \xi)$.Sometimes it can be useful to look at the phase angle corresponding to the $t_i$ time maximizing $\ddot{u}_{RSS}(T_i, t_i, \xi)$.

### *2.4 Larger*

A commonly used measure used for obtaining GMPEs is *Larger*. For each period, this IM is determined by choosing the larger value of the spectral ordinates of the N-S and E-W as-recorded components

(Equation 9) (Beyer and Bommer, 2006, Bradley and Baker, 2015, Boore and Kishida, 2017).

$$Sa_{Larger}(T_i, \xi) = \max[\mathrm{Sa}_{EW}(T_i, \xi), \mathrm{Sa}_{NS}(T_i, \xi)] \quad (9)$$

where $\mathrm{Sa}_{EW}(T_i, \xi)$ and $\mathrm{Sa}_{NS}(T_i, \xi)$ refer to spectral accelerations of the as-recorded horizontal components for each oscillator period $T_i$ and fraction of the critical damping factor, ξ. This measure was one of the most used in the development of GMPEs before the use of GM showed to produce better results in the regressions used in the GMPE calculations.
With the aim of reducing the epistemic uncertainty of this IM, the following sensor orientation-independent IM, related to *Larger*, is proposed.

### *2.4.1 LRotDpp*

In this IM, "L" refers to the *Larger* measure, "pp" to the desired percentile and "D" means period dependent. This measure is defined according to the method proposed by Boore *et al.* (2006) and Boore (2010) for other IMs. In the same way as the RotDpp orientation-independent IMs, linear combinations of the two perpendicular horizontal components are obtained by rotating angles between 0 and 180°. Increments of 1° and Equations 2 and 3 are used. For each rotation angle the two response spectra corresponding to the linear combinations of Equations 2 and 3 are estimated; then the maximum spectral acceleration value is selected for each period, (Equation 9), obtaining a single response spectrum for each non-redundant angle. Once the 180 response spectra are calculated, the corresponding angle of the desired percentile is defined for each period, not being able to identify a single angle for all periods, so that this IM is dependent on the period.

## ***2.5 Combining time histories***

In general, maxima of the rotated responses are combined, regardless of whether these measures are simultaneous or not. Thus, for instance, in the simple case of PGA, the GM of the PGA of the two as-recorded accelerograms, can be, and in fact is, different of the maximum of the time history made by the GM of the accelerograms. As a matter of fact, combining maximum values would be conservative in front of the peak of the combined time histories. The same holds for acceleration damped response time histories. In this research, IMs resulting from the combination of the acceleration responses of two orthogonal horizontal accelerograms are defined and analysed too. Namely, mGM, mGMRotDpp and mGMRotIpp are discussed. The added "m" indicates that the IMs corresponds to maximum values of the combined time histories.

### *2.5.1 mGM, mGMRotDpp and mGMRotIpp*

The IM mGM, is defined as the response spectrum corresponding to the maximum value of the geometric mean of the time histories responses for each oscillator period of a single degree-of-freedom, using the two as-recorded horizontal components (θ = 0), Equation 10.

$$Sa_{mGM}(T_i, \xi, 0) = max\left[\sqrt{|\ddot{u}_{acc1}(T_i, t_i, \xi, 0)| \cdot |\ddot{u}_{acc2}(T_i, t_i, \xi, 0)|}\right] \quad (10)$$

where $\ddot{u}_{acc1}(T_i, t_i, \xi, 0)$ and $\ddot{u}_{acc2}(T_i, t_i, \xi, 0)$ are the time histories acceleration responses for the two linear combinations of Equations 2 and 3 for an oscillator period $T_i$, time $t_i$ and a critical damping factor ξ.
mGMRotDpp and mGMRotIpp, are defined following the same methodology to determine GMRotDpp and GMRotIpp respectively. The significant difference is that the combination of the components is performed before obtaining the maximum response. To calculate mGMRotDpp and mGMRotIpp, the response spectra are computed according to Equation 10, for a range of 0 to 90° with increments of 1°. Then the spectral values are sorted for each oscillator period and the measures for the desired percentile are selected. For the independent one, mGMRotIpp, a penalty function (Equation 11) is used to

determine a single response spectrum corresponding to a unique rotation angle, corresponding to the minimum of the penalty function.

$$penalty(\theta) = \frac{1}{N_{per}} \sum_{i=1}^{h} \left[ \frac{Sa_{mGM}(Ti, \xi, \theta)}{Sa_{mGMRotDpp}(Ti, \xi)} - 1 \right]^2 \tag{11}$$

$$Sa_{mGMRotIpp}(Ti, \xi) = Sa_{mGM}(Ti, \xi, \theta_{min}) \tag{12}$$

where the range of usable periods are $T_1$ to $T_h$, $Sa_{mGM}(Ti, \xi, \theta)$ is the response spectrum of the GM of the time history for a period $Ti$ computed for rotation angle θ, and $Sa_{mGMRotDpp}(Ti, \xi)$ is the $pp^{th}$ percentile value of $Sa_{mGM}(Ti, \xi, \theta)$ over all non-redundant angles. Recall that ξ is the fraction of critical damping.

### *2.6 Summary of IMs*

Table 1 shows the IMs used in this research to define the directionality parameters. Two percentiles were computed: $50^{th}$ for the median response and $100^{th}$ for the maximum response.

Table 1. Summary of ground-motion IMs used in this study

| **Symbol** | **Definition*** |
|---|---|
| N-S, E-W | As-recorded horizontal orthogonal components. |
| GM | Geometric mean of as-recorded horizontal components. |
| GMRotD50 | Median value of the geometric mean of the two horizontal components rotated onto all non-redundant angles (Boore *et al*., 2006). |
| GMRotI50 | GMRotD50 approximation with a constant axis orientation for all the considered periods, obtaining a median value of the geometric mean of the two horizontal components rotated onto all non-redundant period-independent angles (Boore *et al*., 2006). |
| RotD50 | Median value of response spectra of the two horizontal components rotated onto all non-redundant azimuths (Boore, 2010). |
| RotD100 | Maximum value of response spectra of the two horizontal components rotated onto all non-redundant azimuths (Boore, 2010). |
| RSS | Root-sum-of-squares of the time histories of acceleration response (Hidalgo *et al*., 2017). |
| Larger | The larger of the two as-recorded horizontal components (Beyer and Bommer, 2006, Bradley and Baker, 2015, Boore and Kishida, 2017). |
| LRotD50 | Median value of the larger of the two horizontal components rotated through all non-redundant angles. |
| LRotD100 | Maximum value of the larger of the two horizontal components rotated through all non-redundant angles. |
| mGM | Maximum of the time histories responses geometric mean for each oscillator period using as-recorded components. |
| mGMRotD50 | Median value of the mGM rotated onto all non-redundant angles. |
| mGMRotI50 | mGMRotD50 approximation with a constant axis orientation for all the considered periods, obtaining a median value of the mGM rotated onto all non-redundant period-independent angles. |

* The definitions apply for peak ground acceleration (PGA) and response spectral acceleration (Sa).

## 3. GROUND MOTIONS DATABASE

The database used for this research consists of acceleration registers of earthquakes from Italy between 1974 and 2017. This database was collected and standardized using the records of the Italian Accelerometric Archive (ITACA, Luzi *et al.*, 2016a). Records of events after December 31st, 2015, were downloaded from the Engineering Strong-Motion Database (ESM, Luzi *et al*., 2016b) and were added to the database. The complete database, has a total of 1583 three-component acceleration records, for a total of 222 earthquakes recorded in 405 stations. For each record, information on the event (magnitude, location, fault mechanism, etc.) and on the accelerometric station (epicentral distance, site condition, location, etc.) is available.

One of the aims of this study is to estimate different IMs, based on the 5% damped elastic response spectra. With this purpose, after baseline correction and band-pass filtering, a rigorous selection procedure was applied to the strong motion recordings. The following criteria were applied for the selection: depth ($h \leq 30$ km), local magnitude ($M_L \geq 4$) and epicentral distance ($\Delta \leq 50$ km). The local magnitude ($M_L$) was used since it's available for all earthquakes. After applying the selection, 949 records corresponding to 131 earthquakes and 249 stations (Figure 1) were available with a usable period range from 0.01 to 4 seconds for the two horizontal components. The site conditions were revised using the characterization proposed by Felicetta *et al*. (2017).

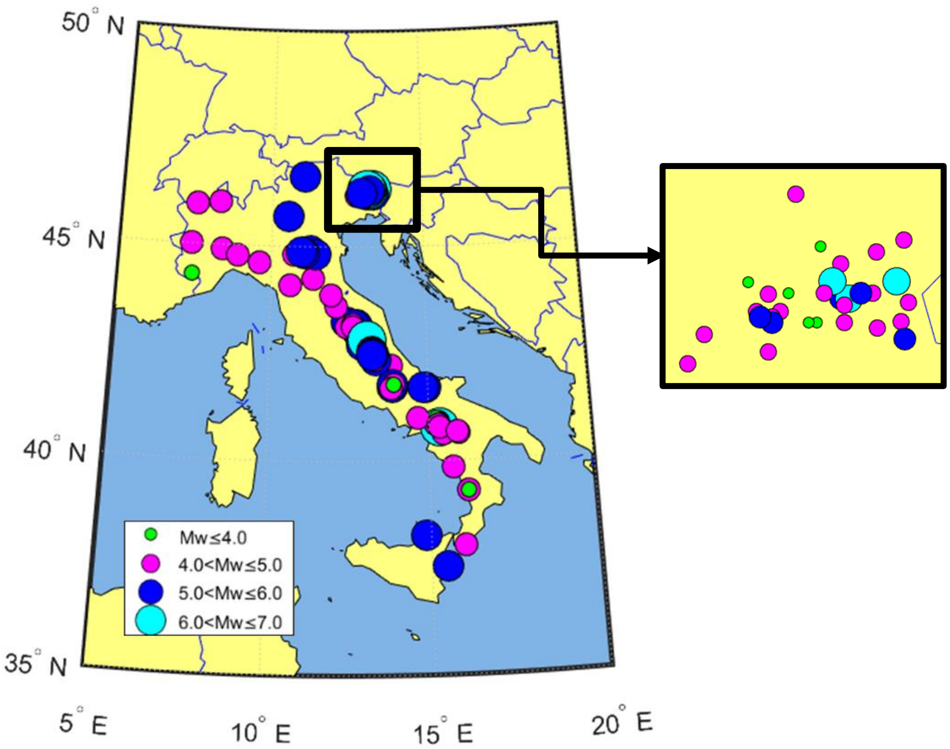


Figure 1. Epicenters and magnitudes of the earthquakes used in this study.

## 4. RESULTS

In order to explain the computations involved in this study, a strong motion record from Umbria earthquake (Oct. 30, 2016) was used. Figure 2 shows the three orthogonal acceleration components with their corresponding 5% damped response spectra.

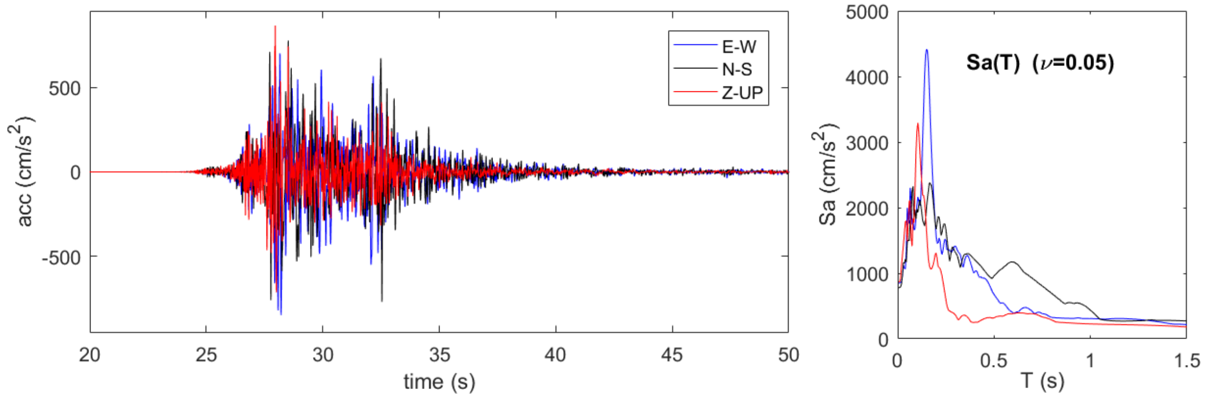


Figure 2 Acceleration components and 5% damped response spectra. Umbria earthquake, Oct. 30, 2016.

Figure 3 shows the combination of the responses (5% damped) of the two horizontal components for an oscillator period of 0.01s, using the measures RSS, GM, Larger, EW and NS. When plotting the maximums (max.), we can observe that the maximum values of the horizontal components (EW and NS), does not coincide at the same time instant. Generally, the GM of the response spectra of the horizontal components is used in the GMPEs, which is estimated with a combination of the maxima of each component. This creates a nonconformity, since, when the maximum values do not coincide at the same instant of time, the physical sense of this combination is lost.
In the other hand, we can see that, for each time instant, the RSS measure is the maximum response, thus following the work published by Hidalgo-Leiva *et al*. (2017). Regarding the maximum value of Larger, it will always match the maximum of one of the two horizontal components, due to their properties.

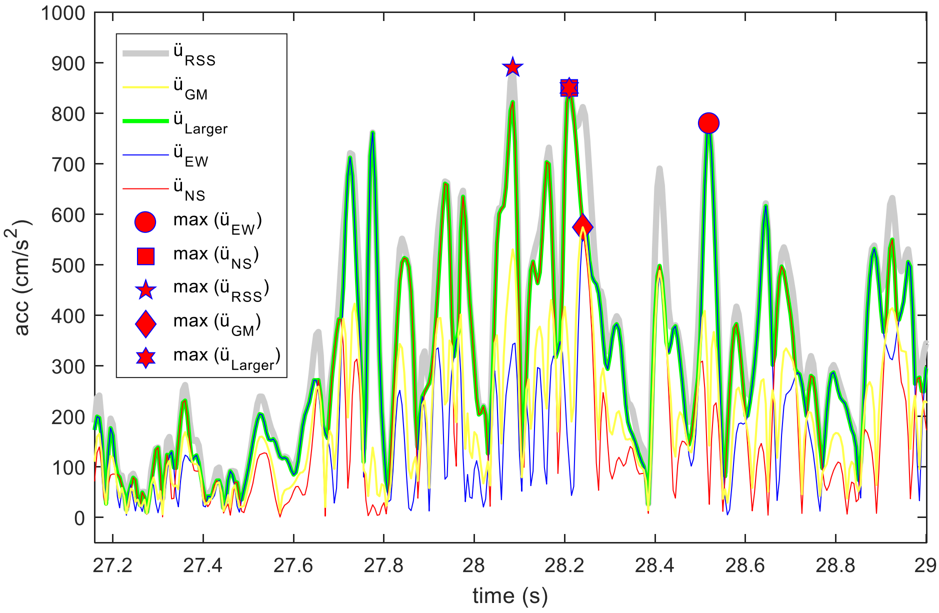


Figure 3. Combination of time histories responses for a single degree-of-freedom oscillator (T=0.01s and 5% of critical damping) using RSS, GM, Larger, EW and NS IMs. Umbria earthquake, Oct. 30, 2016.

In the Figure 4a, the response spectrum for RSS, Larger, mGM and GM of as-recorded horizontal components were computed. Clearly, the $Sa_{RSS}$ shows the maximum value in each period followed by the $Sa_{Larger}$. Comparing the $Sa_{mGM}$ and the $Sa_{GM}$ confirms that the $Sa_{GM}$ IM is conservative. In Figure 4b the NS and EW response spectra are added. The $Sa_{NS}$ is higher than $Sa_{EW}$ for almost all the periods. For this reason, in this case, the $Sa_{Larger}$ is practically the same as $Sa_{NS}$.

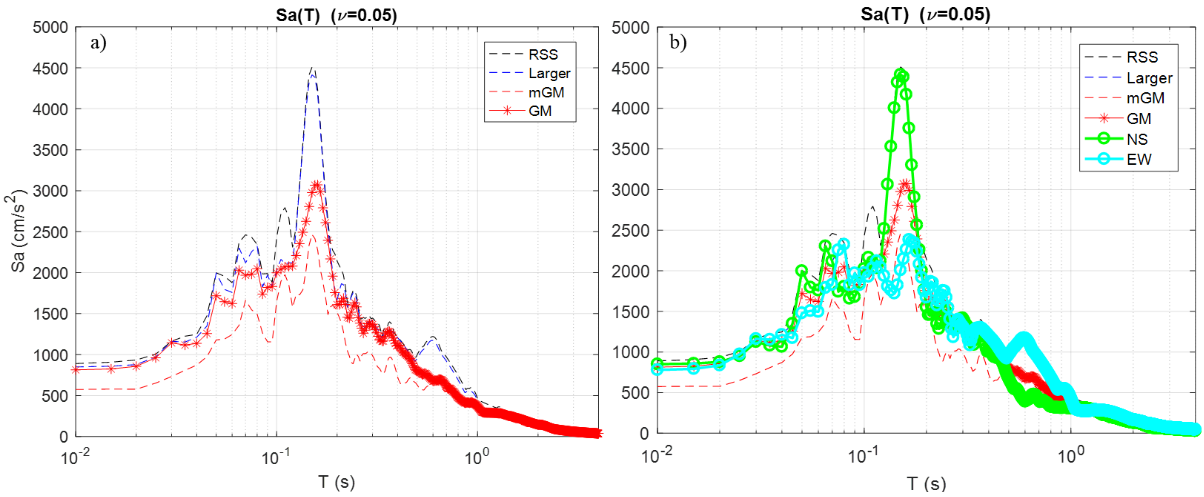


Figure 4. a) 5% damped response spectra calculated with RSS, Larger, mGM and GM as-recorded IMs; b) 5% damped response spectra calculated with RSS, Larger, mGM, GM, NS and EW as-recorded IMs. Umbria earthquake, Oct. 30, 2016.

The independent-orientation IMs were evaluated and compared with the obtained combining the as-recorded ones. In Figure 5 the following three distinct groups can be seen: a combination of time histories (black), median spectral values (red) and maximum spectral values (blue). The orientation-independent median measures ($50^{th}$ percentile) show a good agreement with their similar as-recorded values, mGM with mGMRotD50 and mGMRotI50, GM with GMRotD50, GMRotI50 and RotD50 and Larger with LRotD50.
The $Sa_{RSS}$ has the same values as $Sa_{RotD100}$ for every period, obtaining equivalent results as those obtained by other authors (Hidalgo *et al*., 2017). But also, the $Sa_{LRotD100}$, presented in this paper, has the same values as $Sa_{RSS}$, indicating a new way to obtain the maximum spectral response.

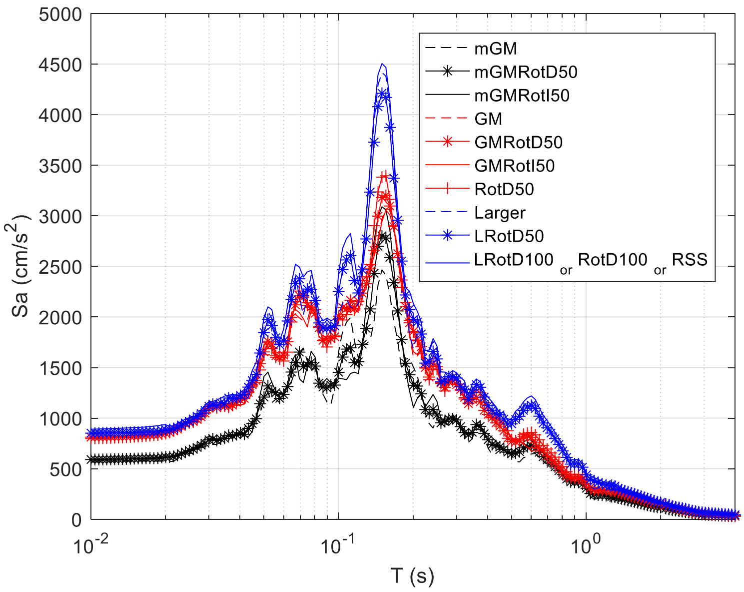


Figure 5. 5% damped response spectra calculated with RSS, Larger, LrotD50, LrotD100, GM, GMRotD50, GMRotI50, RotD50, RotD100, mGM, mGMRotD50 and mGMRotI50 IMs. Umbria earthquake, Oct. 30, 2016.

### *4.1 Ratios*

To compare the IMs, a massive calculation of the 949 selected records was performed, using a program developed in MATLAB by Pinzón (2014). First, the 5% damped acceleration response spectra were obtained of all records and for all the linear combinations considered with the rotation angle variation.

Subsequently, the different sensor orientation-independent measures were calculated, following the methodology described above. For the calculation of the mean ratios, the antilogarithm of the average of the natural logarithms of the ratios was used, which represents the GM of the ratios (Shahi and Baker, 2014). The ratios of all IMs were calculated in function of the GM, for the range period [0.01-4] s, from the considered Italian dataset. The GM of the as-recorded accelerograms was used as a divisor because this is the most commonly used measure.

Instead of combining maximum values of the time series, the study has also been performed by using maximum values of the time histories resulting from different ways of combining the two motion orthogonal components: mGM, mGMRotDpp and mGMRotIpp. Figure 6a illustrates the ratios of $Sa_{mGM}/Sa_{GM}$, $Sa_{mGMRotD50}/Sa_{GM}$ and $Sa_{GMRoI50}/Sa_{GM}$. As pointed out above, $Sa_{GM}$ is conservative when compared with $Sa_{mGM}$. Moreover, our results show that the ratios between the 50$^{th}$ percentile of these orientation independent intensities and the GM of the maximum values of the as-recorded components, are in the ranges 0.78-0.85 and 0.79-0.86 respectively, indicating that the values obtained with GM are conservative.

The results in Figure 6b indicate that the ratios between the independent-orientation measures of median response, $Sa_{GMRotD50}$, $Sa_{GMRotI50}$ and $Sa_{RotD50}$ and the $Sa_{GM}$ of the as-recorded components are close to 1% for GMRotD50 and in the ranges 2-6%, and 1-2% respectively, for RotD50 and GMRotI50. Differences increase with increasing periods. These three ratios show a good agreement with similar studies in other regions (Boore *et al*., 2006, Boore, 2010, Shahi and Baker, 2014, Bradley and Baker, 2015).

Finally Figure 6c display the results of the ratios $Sa_{Larger}/Sa_{GM}$, $Sa_{LRotD50}/Sa_{GM}$ and ($Sa_{RSS}$ or $Sa_{RotD100}$ or $Sa_{LRotD100}$)/$Sa_{GM}$. The value of the ratio between Larger and GM varies between 14% and 25%, similar results were obtained by Bradley and Baker (2015). For the LRotD50, the ratio is in the range 15-27%, varying about 1% compared to Larger. No previous information is available on LRotD50.

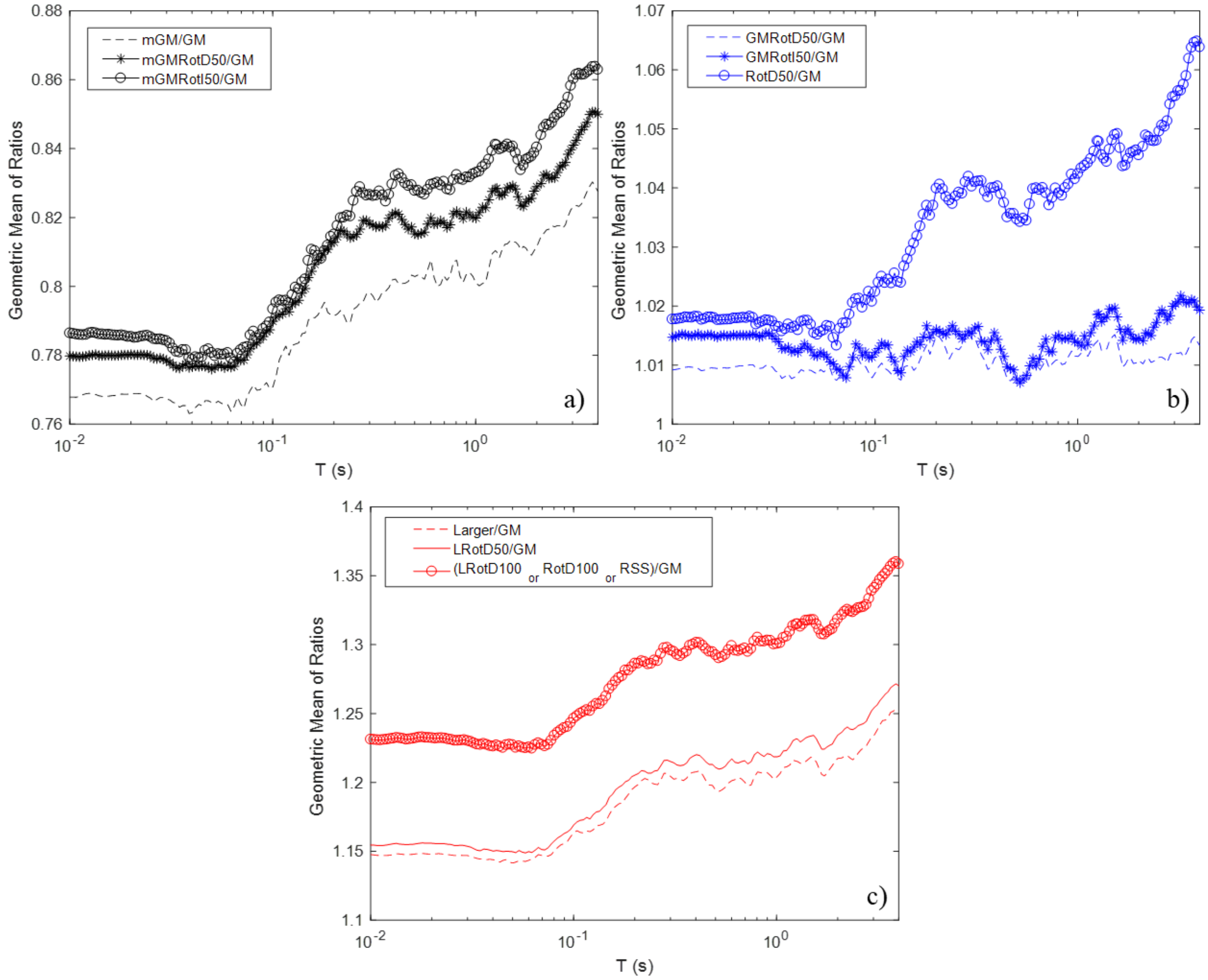


Figure 6. a) Ratios $Sa_{mGM}/Sa_{GM}$, $Sa_{mGMRotD50}/Sa_{GM}$ and $Sa_{GMRotI50}/Sa_{GM}$ from the Italian database; b) Ratios $Sa_{GMRotD50}/Sa_{GM}$, $Sa_{GMRotI50}/Sa_{GM}$ and $Sa_{RotD50}/Sa_{GM}$ from the Italian database; c) Ratios $Sa_{Larger}/Sa_{GM}$, $Sa_{LRotD50}/Sa_{GM}$ and ($Sa_{LRotD100}$ or $Sa_{RotD100}$ or $Sa_{RSS}$)/$Sa_{GM}$ from the Italian database.

We confirm that the maximum value of the RSS of the two orthogonal components is angle and period independent. Our results show that RSS is equal to RotD100 and LRotD100, and the ratios are in the range 23-36%. To compare these maximum values with the obtained by other authors, we made the ratio using as divisor GMRotI50 (Figure 7). The results present a good agreement compared to other investigations (Beyer and Bommer, 2006, BSSC, 2009, Campbell and Bozorgnia, 2007, Huang *et al*. 2011, Watson-Lamprey and Boore, 2007). The first part of the curve is flat around a value of 1.20 and increases to 1.32 at 4.0 s period.

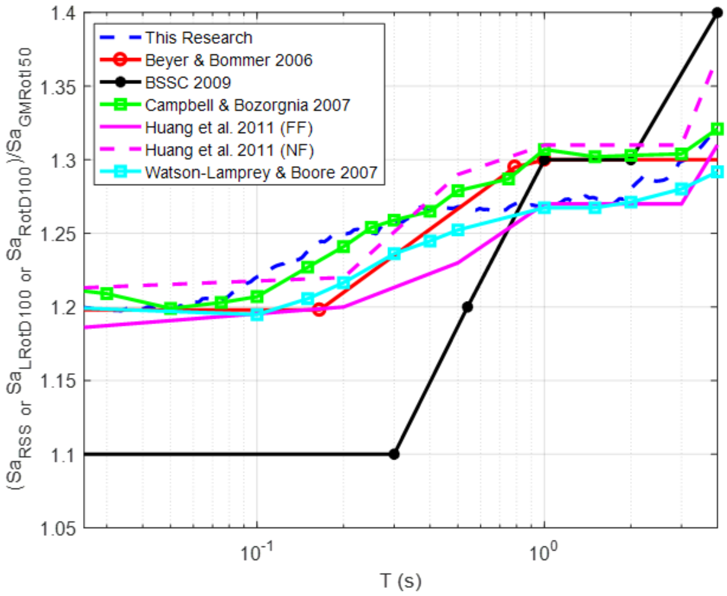


Figure 7. Geometric mean value of the ratio ($Sa_{LRotD100}$ or $Sa_{RotD100}$ or $Sa_{RSS}$)/$Sa_{GMRotI50}$ from the Italian database and other research.

To see if the magnitude influences the results, an analysis with a different range of magnitude was performed. The study was made for the ranges: $4 \leq M_L < 5$, $5 \leq M_L < 6$ and $M_L \geq 6$. A significant result was obtained; the differences between the median and the maximum measures decrease with magnitude; ratios between RSS and GMRotI50 are in the range 1.24-1.34 for magnitudes in the range [4, 5) and they are in the range 1.17-1.30 for magnitudes greater than 6; for the three magnitude ranges analyzed, these ratios increase with the period. However, for different magnitude ranges, differences among ratios are higher for short periods, being smaller at larger periods (Figure 8).

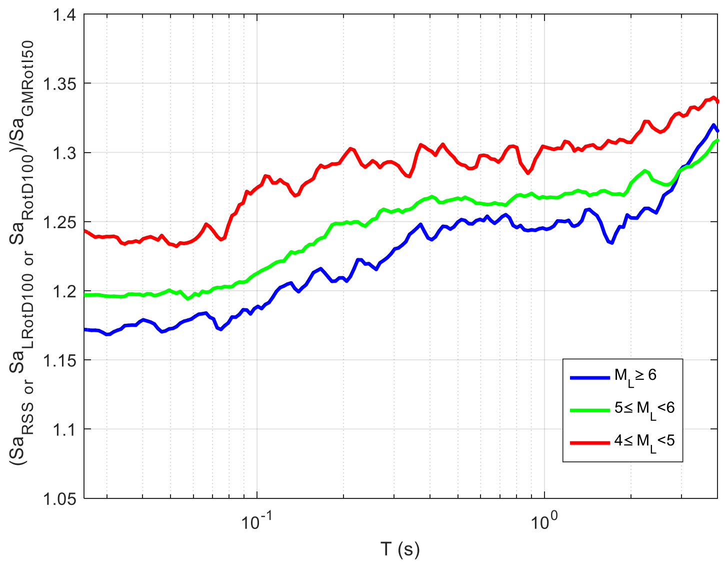


Figure 8. Geometric mean of the ratio ($Sa_{LRotD100}$ or $Sa_{RotD100}$ or $Sa_{RSS}$)/$Sa_{GMRotI50}$ computed for magnitude ranges: $4 \leq M_L < 5$, $5 \leq M_L < 6$ and $M_L \geq 6$, using the Italian database.

## 5. DISSCUSION AND CONCLUSIONS

The theoretical advantage of the orientation-independent IMs is that they eliminate the sensor orientation effect as a contributor to the epistemic uncertainty. The results obtained in this study are of great interest in the development of GMPEs in seismic hazard studies. This type of studies requires a high computational effort, but ratios found in this can be used for this specific database, to approximate the spectral accelerations from one measure to another, without having to perform all calculations massively again and, consequently, without the need to recalculate the GMPEs.
The IMs GMRotD50, GMRotI50 and RotD50 are usually larger than the GM as-recorded, in addition to being sensor orientation-independent. It is noteworthy that both GMRotI50 and RotD50 have been used by the Pacific Earthquake Engineering Research Center (PEER) NGA GMPEs as new IMs. Similar results to Boore *et al*. (2006) and Boore (2010) were obtained in this study. The value of GM as-recorded has a variation of only 1% compared to GMRotD50, 1-2% compared to GMRotI50 and 2-6% compared to RotD50 for a range of periods from 0.01 to 4 s. Despite there is a little difference between the GMRotD50, GMRotI50, RotD50 and GM, it is recommended to use these orientation-independent measures as they decrease the epistemic uncertainty in the GMPEs (Beyer and Bommer, 2006).
Moreover, instead of combining maxima, the study was performed also by using maxima of the time histories resulting from different ways of combining the two motion orthogonal components: mGMRotDpp and mGMRotIpp. For these cases, our results indicate that now, ratios between the $50^{th}$ percentile of these orientation independent intensities and the GM of the maximum values of the as recorded components, are in the ranges 0.78-0.85 and 0.79-0.86 respectively, indicating that combining maxima is conservative compared to combining the time histories and obtaining the maximum after.
Another sensor-orientation-independent IM that was investigated in this paper is the related with the Larger measure, named: LRotDpp. Our results indicate that the ratios between Larger and LRotD50 and the GM of the as-recorded components are in the ranges of 14-25% and 15-27% for Larger and LRotD50 respectively. Showing that differences increase with increasing periods. No previous information is available on LRotDpp.
Several studies have analyzed the quadratic composition of the maximal response (Beyer and Bommer, 2006, BSSC, 2009, Campbell, 2007, Huang and Whittaker, 2011, Watson-Lamprey and Boore, 2007, Pinzon *et al.*, 2015 and Hidalgo *et al.*, 2017). In this paper we have performed the exercise of calculating the vector combination of the two orthogonal time histories ie RSS, and it was found that has the same results as RotD100 and LRotD100. When comparing RSS/GMRotI50 ratio, very similar values were obtained compared to those cited above. For all cases, except for the expression proposed by the NEHRP (BSSC, 2009), the RSS/GMRotI50 ratio is constant in low periods, with an approximate value of 1.20, increasing until 1.32 in long periods. A remarkable result was obtained when comparing different ranges of magnitude: differences between median and maximum measures decrease with increasing magnitudes; ratios between RSS and GMRotI50 are in the range 1.24-1.34 for magnitudes in the range [4-5] and they are in the range 1.17-1.30 for magnitudes greater than 6; for the three magnitude ranges analyzed, these ratios increase with the period. However, for different magnitude ranges, differences among ratios are greater for short periods, being smaller for large periods.
The calculation of RSS, RotD100 and LRotD100 can be considered as the maximum possible response, corresponding to the most unfavorable case. Consequently, these values can be used for the design or risk assessment of structures of special importance such as historical-cultural heritage buildings or other high-risk constructions, since it is possible to calculate the maximum value for the available database, representing the $100^{th}$ percentile of all possible spectra for the available database.

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